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Simulated Molecular Gas Emission in Galaxy Mergers with Embedded AGN

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Abstract. We investigate the effect of embedded active galactic nuclei (AGN) in galaxy mergers on the CO molecular line emission by combining non-local thermodynamic equilibrium (LTE) radiative transfer calculations with hydrodynamic simulations. We find that AGN feedback energy in gas rich galaxy mergers can contribute to large molecular outflows which may be detectable via velocity-integrated emission contour maps, as well as through kinematic features in the emission line profiles.

1. Introduction

Galaxy mergers in the Universe produce a prodigious amount of infrared luminosity due to dust heating by a combination of the induced starburst activity, and possibly an enshrouded active galactic nucleus (AGN). The remnant galaxies, often dubbed ultraluminous infrared galaxies (ULIRGs, $L_{\rm IR} \geq 10^{12} L_{\odot}$), may represent a crucial point in an evolutionary sequence of galaxy formation. While ULIRGs are known to host violent starbursts, they may also serve as antecedents to quasars. Observations have shown that ULIRGs can exhibit spectral energy distributions (SEDs) characteristic of both starburst galaxies, and quasars (Farrah et al. 2003). Recent models have added a theoretical foundation for the starburst-AGN connection. Springel, Di Matteo & Hernquist (2005) and Hopkins et al. (2005a,b) have shown that there may be a link between the merger induced starburst and an AGN dominated phase. In this model, feedback energy associated with the growth of the central black hole(s) (BH) can lift the veil of obscuring dust and gas, and reveal, along several sightlines, an optically selected quasar.

There has been a longstanding interest in understanding emission from the molecular gas in ULIRGs, as the molecular gas serves as the fuel for the starburst activity, and possibly for accreting BH(s). Most ULIRGs in the local Universe have been shown to emit copious molecular line radiation, both in diffuse and dense form (e.g. Sanders, Scoville & Soifer, 1991, Narayanan et al. 2005). Recent studies by Greve et al. (2005), Hainline et al. (2005), Carilli et al. (2005) and Tacconi et al. (2006) have shown that IR bright galaxies at high redshift ($z \sim 2$)

contain a significant amount of molecular gas as well. As evidenced by X-ray and infrared (IR) studies, many of these galaxies at high-z are known to contain AGN (Alexander et al. 2005, Polletta et al. 2005). In this contribution, we discuss the possible impact of embedded AGN on the observed molecular line emission in galaxy mergers.

2. Numerical Methods: SPH and non-LTE Radiative Transfer

We have carried out hydrodynamic simulations with an improved version of the smooth particle hydrodynamics (SPH) code, GADGET-2 (Springel, 2005; Springel et al 2005). The code includes a prescription for AGN feedback in which a fraction (0.05 %) of the accreted mass energy onto the central BH(s) is reinjected into the ISM as thermal energy. The code allows for radiative cooling of the gas, a multi-phase structure of the ISM which includes cold clouds embedded in a hot pressure confining ISM, and a prescription for star formation constrained by the Schmidt/Kennicutt laws (Kennicutt, 1998; Schmidt, 1959; see also Springel & Hernquist, 2003).

The progenitor galaxies in the merger simulation presented in this contribution are roughly Milky-way like, but with 50% gas fraction. They are thus likely reasonable representatives of the progenitors of present-day ULIRGs. The dark matter halos were initialized with a Hernquist (1990) profile and the galaxies followed a parabolic orbit, initially separated by 140 kpc. In order to simplify the analysis presented here, we have not included supernovae winds in our models.

Our non-LTE radiative transfer methods are based on an improved version of the Bernes (1979) Monte Carlo algorithm which we more fully describe in Narayanan et al. (2006a,b). Our improvements focus on including giant molecular clouds (GMCs) as singular isothermal spheres in a sub-grid fashion in order more accurately model emission from high excitation lines which originate in the dense cores of molecular clouds. In this study we consider the CO molecular line emission and use $\sim 10^7$ model photons per iteration.

3. Results

3.1. Morphology

We have run two identical simulations, one with BHs, and one without. While the CO morphologies in these galaxies generally follow similar evolutionary paths, there are some distinct differences arising from thermal energy input by the accreting BH(s).

In the merger simulation without BHs, after the galaxies merge, the star formation proceeds on scales of a few kiloparsecs. The starburst continues, relatively unhindered, until most of the cold molecular gas is consumed (Springel et al. 2005). In contrast, when BHs are included in the simulations, the star formation becomes compact soon after the progenitor galaxies coalesce. An AGN driven wind blows the diffuse gas out of the nucleus, leaving behind only a dense core of star forming gas, typically confined to the central 500-1000 pc. These phenomena are quantified in Figure 1, where we show the CO (J=1-0) half-light radius as a function of time for both simulations. Observationally,

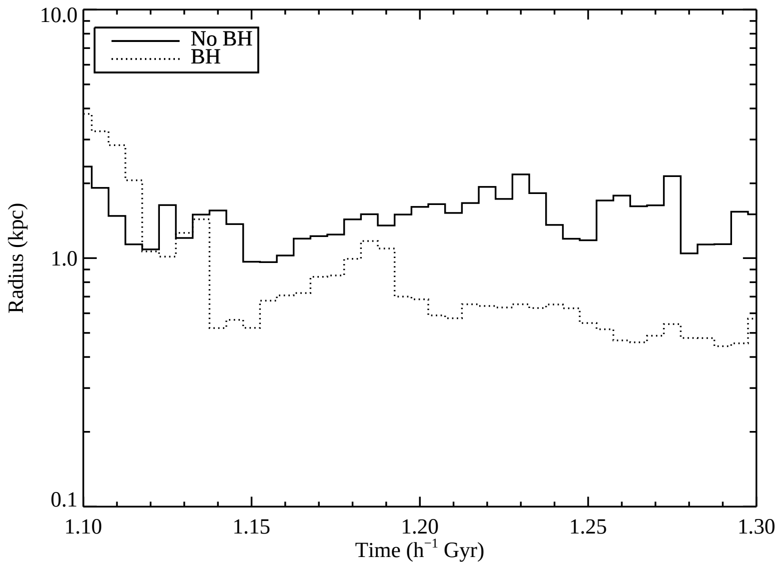

Figure 1. CO (J=1-0) half light radius as a function of time for models of galaxy mergers without (solid line) and with (dash line) black holes. The AGN winds in the black hole model remove the extended diffuse gas around the nucleus, leaving behind only a compact core of dense molecular gas.

CO emission is seen to be heavily concentrated within the central $\sim$1/2 kpc in advanced mergers (e.g. Bryant & Scoville, 1999).

During the period of heaviest black hole accretion, the AGN feedback energy can have a dramatic effect on the CO morphology. In Figure 2, we show CO (J=1-0) emission contours for a series of snapshots from our hydrodynamic simulation with BHs spanning $\sim$60 h^{-1} Myr. The plot traverses a time series beginning when the galaxies are just approaching for final coalescence through the beginning of the phase of maximum BH accretion/feedback. As is evident from T$\sim$1.14 h^{-1} Myr onward, the galaxy system ejects large columns of molecular gas through an AGN-driven wind. These outflows may be imageable via CO emission. While in detail the AGN wind may destroy some clouds owing to thermal conduction, enough gas is entrained in the winds such that a large column of molecular gas survives. These outflows should be imageable with high-density molecular gas tracers as well. Our simulations show significant CO emission from the outflows in the CO (J=3-2) and CO (J=6-5) transitions. Morphological signatures similar to those see in Figure 2 may have been observed in LIRG NGC 985 (Appleton et al. 2001). The simulations we ran without BHs do not show molecular outflows. Additional simulations are needed to investigate whether supernovae winds can drive similar columns of gas.

3.2. Line Profiles

Large scale outflows due to AGN activity may be observable even with low spatial resolution observations through their imprint on the emission line profile. Typically, once the galaxies have merged (in our simulations, when the BHs

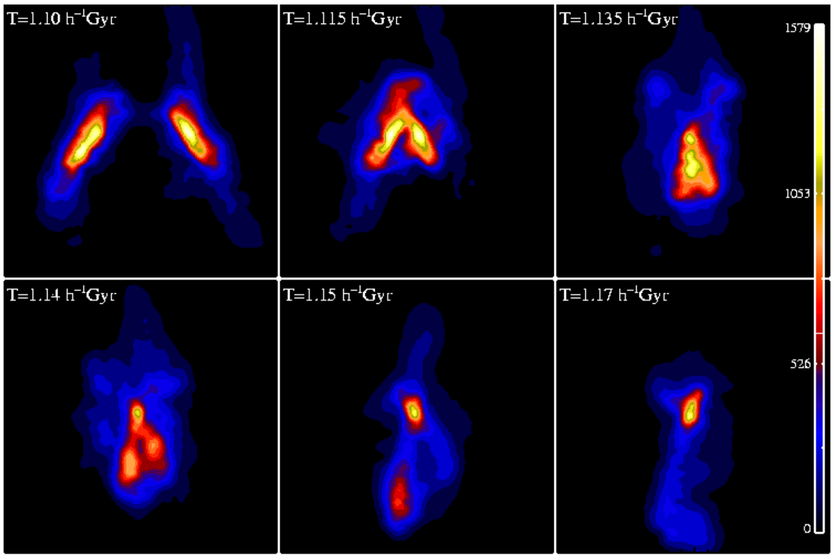

Figure 2. CO (J=1-0) emission contours for an equal mass gas rich galaxy merger. After the galaxies merge, gaseous inflows fuel black hole growth. Subsequent AGN feedback energy can blow large amounts of molecular gas out from the nuclear regions. The time stamp of each image is in the top left of each panel, and the intensity contours are in units of K-km s^{-1}. The scale for the contours is on the right. Each panel is 12 h^{-1}kpc on a side, and the plots are made at 1/4 kpc spatial resolution.

are no longer individually distinguishable), the characteristic CO emission line profile is well described by a single Gaussian, centered at the systemic velocity of the galaxy. However, when viewing outflows with a significant line of sight (LOS) component, a secondary peak can appear in the line profile, red or blueshifted at the LOS velocity of the outflow.

In Figure 3, we show the BH accretion rate as a function of time and a sample of CO (J=1-0) emission line profiles. In an effort to model the spectral emission from an unresolved observation, we have set the merger model at z=2 (Ω_Λ=0.7, Ω_M=0.3, h=0.75), and convolved our simulated observations with a 30$''$ single-dish Gaussian beam. The emission line profiles are modeled such that the observer is viewing the outflow of Figure 2 moving away from them with a large LOS velocity component. Near T=1.16 h^{-1}Gyr , a high velocity narrow peak appears in the emission line. This line profile of a broad Gaussian with a narrow outflow-induced peak appears to be characteristic of outflowing gas along the line of sight in our models. We estimate the "outflow" profile to be visible $\sim$25% of the time, averaged over many viewing angles.

Double peaked profiles are known to exist in mergers in cases that do not necessarily correspond to outflows. Mergers prior to final coalescence exhibit a double peak where the emission peaks originate in the starburst nuclear regions of the progenitor galaxies. Similar profiles also arise in galaxies in which there is significant rotation. The degeneracy between the double-peak or rotation profile, and the "outflow " profile may be removed from the shape of the actual lines, however. From our simulations, the double peak corresponding to molecular

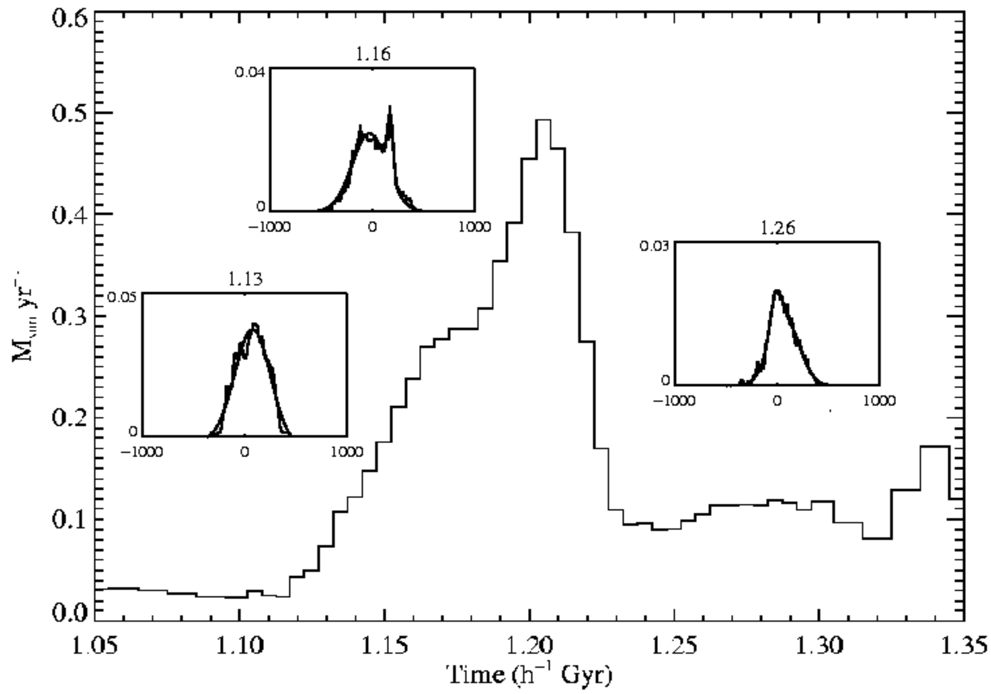

Figure 3. Black hole accretion rate as a function of time for the model with BHs and selected CO (J=1-0) emission line profiles. The line profiles are modeled such that the outflow of Figure 2 is moving away from the observer, along the line of sight. The time associated with each line is above the spectra. The high velocity narrow peak in the emission line at T$\sim$1.16h^{-1}Gyr is indicative of outflowing gas along the line of sight. The y-axis for the spectra is Rayleigh-Jeans temperature, and the x-axis is offset velocity in km s^{-1}. The best double-Gaussian fit for each spectra is over plotted in dashed lines.

outflows is always a broad Gaussian with a narrow peak red or blueshifted from the systemic velocity of the galaxy. The narrow peak can be quite bright due to the high columns along the line of sight, but typically much narrower than the $\gtrsim$500 km s^{-1} characteristic of the accompanying broad-line component owing to small velocity dispersions in the outflow. Conversely, the line profiles originating in an inclined rotating system or from a pre-coalescence merger are typically represented by two broad, symmetric Gaussians, centered about the systemic velocity of the galaxy, and do not have a narrow line component as seen in our simulations with outflows.

The outflows can exhibit high levels of molecular excitation. In Figure 4, we present the emission line profile viewing the outflow in Figure 2 moving along the line of sight in CO (J=1-0) and CO (J=3-2). CO (J=1-0) traces most molecular gas, whereas CO (J=3-2) preferentially is excited in the dense cores of molecular clouds. The component of the emission line due to the gas entrained in the AGN wind remains bright through many high-J transitions, suggesting a possible relevance to observed emission line profiles in high-z mergers.

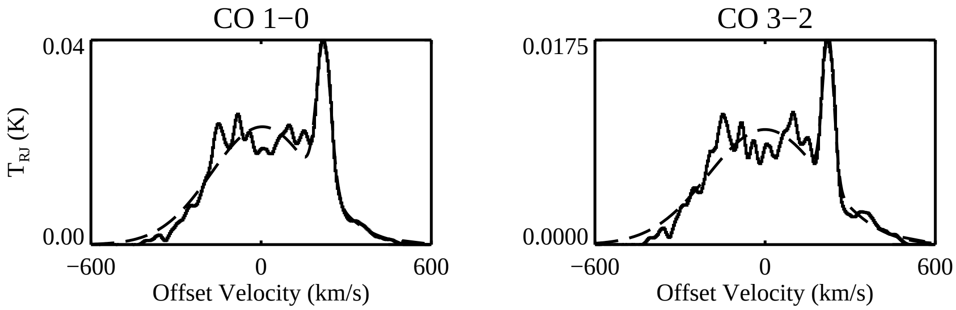

Figure 4. Emission line profiles in CO (J=1-0) and (J=3-2), viewing the T=1.15 h^{-1}Gyr snapshot of Figure 2 such that the outflow is along the line of sight. The high velocity peak is due to outflowing gas, and is visible even in high excitation gas. The best double-Gaussian fit for each spectra is over plotted in dashed lines.

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